MULTIPLE-PATH LINKED COMMON-VIEW TIME TRANSFER (LCVTT)

Wilson G. Reid
SFA, Inc., Largo, MD 20772, USA

Abstract

Analysis of the on-orbit Navstar clocks and of the GPS monitor site reference clocks is performed by the Naval Research Laboratory[1] using post-processed precise ephemerides. The ephemerides are produced by the National Imagery and Mapping Agency (NIMA) for each of the GPS space vehicles from pseudorange measurements collected at five U.S. Air Force (USAF) and at ten NIMA GPS monitor sites spaced around the world. The time reference at the NIMA Washington, D.C., site, which is co-located with the U.S. Naval Observatory precise-time site, is the DoD Master Clock. Hence, it is possible to transfer time via linked common view[1] *every 15 minutes from the DoD master clock to the remaining USAF and NIMA GPS monitor sites. Linking sites serially, although logically simple and computationally efficient, was found to suffer several disadvantages. The most serious of these was the accumulation of gaps in the time transfer to a remote site. A secondary disadvantage was the dominance in the linking process of the short-term noise from a single noisy site. Using multiple common-view paths overcomes both of these defects by supplementing the link that propagated the gap in the data and by providing multiple independent measurements that can be averaged to reduce the measurement noise. An additional benefit of the multiple-path method is an improvement in the continuous coverage*[2] *of the Navstar space vehicle clocks, i.e., in referencing the observations of a space vehicle clock by each of the monitor sites back to the DoD Master Clock. Improvement was manifested by an increase in the number of estimates obtained of the offset of the space vehicle clock from the DoD Master Clock and by a decrease in the short-term noise of these estimates.*

INTRODUCTION

The purpose of the study in reference [1] was to show the following: (1) that time could be transferred every 15 minutes by common view between adjacent GPS monitor sites, (2) that time could be transferred from the DoD Master Clock to a remote site by linking adjacent sites serially from the NIMA Washington, D.C., monitor site, and (3) that by continuing the serial linking in a westerly direction back to the NIMA Washington, D.C., monitor site, the closure obtained would provide a check on the precision of this method of transferring time. A mean phase error of 31 picoseconds obtained by using the 11 monitor sites and the 25 Navstar space vehicles then operational confirmed the precision of the method. The path used in the study reported in 1995 is depicted in Figure 1.

A diagram of the method of combining common-view clock pairs in the serial linking to transfer time from the DoD Master Clock to the remote monitor sites is shown in Figure 2. The

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nomenclature, *e.g.*, CSP-WAS implies the offset of the Colorado Springs ground reference clock from the ground reference clock at the Washington, D.C., monitor site. By adding the offset of the clocks for two common-view clock pairs containing a common clock, *e.g.*, HAW-CSP + CSP-WAS, the intermediate clock, in this case CSP, cancels leaving the linked clock pair HAW-WAS. By successively adding the offset of the clocks for the common-view clock pairs on each line of the diagram, time is transferred serially by linked common view to each of the remote sites and back to Washington for closure.

Subsequently, the method of transferring time from the DoD Master Clock to a remote monitor site was changed to go in both easterly and westerly directions so that the total longitude traversed to any site would not exceed 180°, thereby decreasing the accumulation of gaps in the data. Figure 3 demonstrates how the gaps in the time transfer accumulate with each link. This is a plot of the phase offset of each of the remote ground reference clocks from the DoD Master Clock after removal of the frequency offset (slope of the phase). The scale has been compressed to emphasize the times for which measurements are available. The respective traces have been biased so as to appear one above another on the same set of axes in the order of linking. The bottom trace is a plot of the times for which observations of a Navstar clock were made by the NIMA Washington, D.C., monitor site. These times represent the maximum set of times for which time could be transferred by common view from the DoD Master Clock to the adjacent monitor sites and thence to the more remote sites. In the 10-day period shown here beginning at 0000 UT and ending at 0000 UT, there would be a total of 961 opportunities to make 15-minute observations. On Tuesday, February 2, 1999, a gap of 2 hours (eight measurement times) appears in the trace for the DoD Master Clock beginning at 2200 UT. This gap can be seen to propagate to all subsequent sites. Likewise gaps appearing in the time transfer to Ascension Island on Friday, February 5, 1999 and on Sunday, February 7, 1999 propagate to both England and Bahrain. A large gap in the time transfer to England on Thursday, February 4, 1999 propagates to Bahrain, which suffers from the accumulated gaps from the preceding five sites in the serial linking. Because of the accumulation of gaps in the time transfer from serial linking of the sites, the Bahrain monitor site realized only 831 time transfers from the DoD Master Clock.

By comparison, Figure 4 shows for the same six monitor sites and for the same period of time the observation times populated by each of the sites. The 2-hour gap on Tuesday, February 2 was present in all of the NIMA sites and was attributable to a data distribution problem. Except for England and Ascension Island, which made observations at 898 and 896 of the observation times respectively, the other three remote sites made observations at the same number of observation times as the Washington, D.C., site, *i.e.*, at 953 observation times. Hence, the accumulation of gaps in the time transfers from serial linking resulted in a 13 percent reduction in the number of time transfers from the DoD Master Clock to Bahrain.

PERFORMANCE METRICS

Closer examination of Figure 4 reveals that very few of the gaps in the observation times at Ascension Island are matched by gaps at England. This, considering the high number of observation times populated at Bahrain, suggests that, if multiple paths were used to transfer time to Bahrain, the maximum number of time transfers possible might be achieved. The selection of an optimum configuration of multiple paths to a monitor site presupposes some performance metrics. One of these, the common observation times, is presented in Table 1.

Table 1
Observation Times Populated and Observation Times Common to Washington, D.C. Monitor Site January 31 to February 10, 1999

Monitor Site	Observation Times Populated	Observation Times Common
Alaska	951	951
Argentina	953	953
Ascension Island	951	889
Bahrain	953	953
Beijing	895	895
Colorado Springs	904	897
Diego Garcia Island	790	782
England	898	898
Hawaii	887	879
Kwajalein Island	911	903
New Zealand	953	953
Quito	953	953
Smithfield	950	950
Washington	953	----

This table lists the number of observation times populated at each of the 14 monitor sites and the number of those times that are common to the Washington, D.C. monitor site for the 10-day period from January 31 through February 9, 1999. The number of common observation times for a monitor site constitutes the greatest upper bound on the number of time transfers that can be achieved from the DoD Master Clock at the Washington, D.C., monitor site to the monitor site in question. Two factors that might reduce this bound are the purging of statistical outliers from the observations of a monitor site and the occurrence of some observations at low elevation angles which places them out of common view with adjacent monitor sites. Nevertheless, the percentage of this number of time transfers achieved for the configuration of multiple paths chosen may be used as a figure of merit for that configuration.

Another metric useful in determining the optimum configuration of multiple paths to a site is the average number of space vehicles in common view between the target site and the remaining sites. A large number of space vehicles in common view implies that more time transfers will be achieved and that the measurement noise will be smaller as a consequence of averaging a larger number of raw time transfers, each of which results from one of the space vehicles in common view. This number, listed in descending order in Table 2, was determined by doing common-view time transfer between sites and finding the ratio of raw measurements to smooth measurements for the entire time period of 10 days. The number of time transfers in the table for a given site is sensitive not only to the distance between that site and Bahrain, but also to the number of observation times populated by that site. For example, all 961 observation times had to be populated by both England and Bahrain for the number of smooth time transfers to equal the maximum number possible for the 10-day span. Also, although Diego Garcia Island had the highest average number of space vehicles in common view with Bahrain, the number of time transfers was small because of an outage of 9 days from March 5 to March 14 at that site due to station maintenance. The time span in Table 2 was chosen to enable inclusion of the NIMA monitor site in South Africa for which data first became available March 7, 1999.

Table 2
Average Number of Space Vehicles in Common View between Bahrain and Remaining Monitor Sites
March 7–17, 1999

Monitor Site	Number of Smooth Time Transfers	Number of Raw Time Transfers	Number of Space Vehicles in Common View
Diego Garcia Island	272	1544	5.68
England	961	5254	5.47
Beijing	961	4590	4.78
South Africa	938	4064	4.33
Alaska	960	3124	3.25
Ascension Island	939	3025	3.22
Washington	936	1782	1.90
Smithfield	876	1518	1.73
Kwajalein Island	692	982	1.42
Quito	619	760	1.23
Argentina	602	700	1.16
Colorado Springs	679	750	1.10
Hawaii	211	211	1.00
New Zealand	39	39	1.00

PATH CONFIGURATION

The desired algorithm for transferring time from the DoD Master Clock would, of necessity, begin by transferring time to the sites nearest the Washington, D.C., site and, from these, would transfer time to the more remote sites. Time would be transferred first in a westerly direction to the most remote site within 180° longitude of Washington, D.C., which is Beijing. Time would then be transferred in an easterly direction to the most remote site within 180° longitude of Washington, D.C., which is Diego Garcia Island. An evaluation was first made of the performance of the common-view time transfer from the Washington, D.C., monitor site to the remaining fourteen monitor sites, as shown in Table 3, which lists the remote sites in descending order of the number of space vehicles in common view. The number of observation times common to the Washington, D.C., site and a remote site is identical, in this case, to the number of observation times populated by the remote site. This relationship obtains by virtue of the fact that the Washington, D.C., site populated all 961 observation times possible in the 10-day time period. The first four sites in the list, all with 4.84 space vehicles or more in common view, realized the maximum number of time transfers possible utilizing the single common-view path. The other sites fell short of this goal by amounts that increased with distance from Washington, D.C. These sites must, therefore, be linked with intermediate sites if the maximum number of time transfers possible, in this case assumed to be the number of observation times populated by the remote site, is to be realized. With the linking comes the possibility of propagating gaps in the time transfer, which, as argued above, could be avoidable by supplementing the paths propagating the gaps.

Table 3
Performance of Common View Time Transfer from Washington, D.C. Monitor Site to Remaining Monitor Sites
March 15–25, 1999

Monitor Site	Observation Times Populated	Number of Smooth Time Transfers	Number of Raw Time Transfers	Number of Space Vehicles in Common View
Colorado Springs	956	956	6228	6.51
Quito	961	961	5652	5.88
Alaska	961	961	5479	5.70
England	961	961	4652	4.84
Hawaii	957	956	3017	3.16
Ascension Island	921	900	2816	3.13
Argentina	961	955	2796	2.93
Bahrain	961	942	1797	1.91
Beijing	953	849	1518	1.79
Kwajalein Island	927	764	1169	1.53
South Africa	939	635	890	1.40
New Zealand	961	399	465	1.17
Diego Garcia Island	953	133	133	1.00
Smithfield	961	0	0	0
Washington	961			

MULTIPLE PATHS

The analysis leading to selection of multiple paths to Bahrain for the period of January 31 to February 10, 1999 is typical of the process used to identify the multiple paths used in the algorithm for multiple-path linked common-view time transfer (LCVTT) and includes some interesting details. From Table 2 the best candidates for multiple paths to Bahrain are those listed at the top of the table with the largest number of space vehicles in common view. Although the site on Diego Garcia Island had the greatest number of space vehicles in common view, that path is used as one of the multiple paths in transferring time to that site. The next five sites in the list are logical choices because of the large number of space vehicles they have in common view with Bahrain.

These five paths are illustrated in Figure 5. Alaska would not appear from the Mercator projection to be a good candidate because of the apparent large distance from Bahrain. However, the great circle distance over the pole places it close enough to Bahrain that both Alaska and Ascension Island have about the same number of space vehicles in common view with Bahrain. Because the time transfers are computed first in the westerly direction, the time transfer from Washington to Beijing is available for linking with Bahrain, even though they are on opposite sides of the meridian marked with a dotted line as halfway, or 180° removed, from Washington. Figures 6 and 7 are a comparison of the time transfer from Washington to Bahrain based on single-path and on multiple-path linking. For the single path, there were 831 time transfers realized out of a possible 953, or 87.2 percent achieved. For the multiple paths, the time transfers realized increased to 952, or 99.9 percent achieved. By averaging multiple independent estimates of the time transfer from the multiple paths, the Allan deviation for a sample time of 15 minutes decreased from 1.93 pp 10^{12} to 1.03 pp

10^{12}. This can be seen in Figure 7 as decreased scatter in the 15-minute measurements. It is instructive to note that, for the 10 days covered by Figure 7, the only monitor sites transferring time to Bahrain were England, Ascension Island, and Beijing. The monitor site in South Africa was not yet operational, and the monitor site in Alaska was not used, since four paths appeared to be adequate. Although the three sites contributed only 898, 881, and 894 time transfers respectively, the resulting time transfers to Bahrain totaled 952, which shows clearly the significance of the multiple paths in linked common-view time transfer.

Figure 8 demonstrates the effect on the Continuous Coverage of the propagation of gaps in the time transfer resulting from single-path linked common-view time transfer. Efforts to obtain a continuous history of the offset of the Navstar 30 timing signal from the DoD Master Clock were hampered by gaps in the time transfers to the remote sites. The observations of the Navstar 30 timing signal by sites suffering gaps in the time transfer could not be referenced back to the DoD Master Clock at those times for which the time transfers were missing. As a result, only 896 out of a possible 953, or 94.0 percent, of the estimates of the phase offset were obtained. With the use of multiple-path linked common-view time transfer, this number increased to 952, or 99.9 percent, as shown in Figure 9. The Allan deviation at the basic sample rate of 15 minutes also decreased from 1.70 pp 10^{12} to 1.30 pp 10^{12}, demonstrating improvement in the measurement noise.

Figure 10 shows the common-view links used in the new algorithm for the multiple-path linked common-view time transfer. This configuration is valid only for the present set of 15 monitor sites. As other NIMA monitor sites are added, not only will common-view links to the new sites be required, but the optimum configuration of links to surrounding sites would be expected to change.

CONCLUSION

A new algorithm has been derived for Linked Common-View Time Transfer (LCVTT) from the DoD Master Clock at the NIMA Washington, D.C., monitor site to the remaining five USAF and nine NIMA monitor sites. The new algorithm uses multiple paths to supplement links that would otherwise propagate gaps in the time transfers. An additional advantage of the new algorithm is a reduction in the measurement noise resulting from the averaging of multiple, independent time transfers from multiple links to a given site. These same advantages accrue to the estimation of the offset of a Navstar clock from the DoD Master Clock, i.e., to Continuous Coverage, which uses the time transfer to a remote site to reference the observations of the Navstar clock by that site to the DoD Master Clock.

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[1] W. G. Reid, T. B. McCaskill, O. J. Oaks, J. A. Buisson, and H. E. Warren 1996, *"Common View Time Transfer Using Worldwide GPS and DMA Monitor Stations,"* Proceedings of the 27th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 29 November-1 December 1, 1995, San Diego, California, USA, pp. 145-158.

[2] W. G. Reid 1997, *"Continuous Observation of Navstar Clock Offset from the DoD Master Clock Using Linked Common View-Time Transfer,"* Proceedings of the 28th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 3-5 December 1996, Reston, Virginia, USA, pp. 397-408.

PATH OF LINKED COMMON-VIEW TIME TRANSFER USING USAF AND NIMA GPS MONITOR STATIONS OPERATIONAL IN 1995

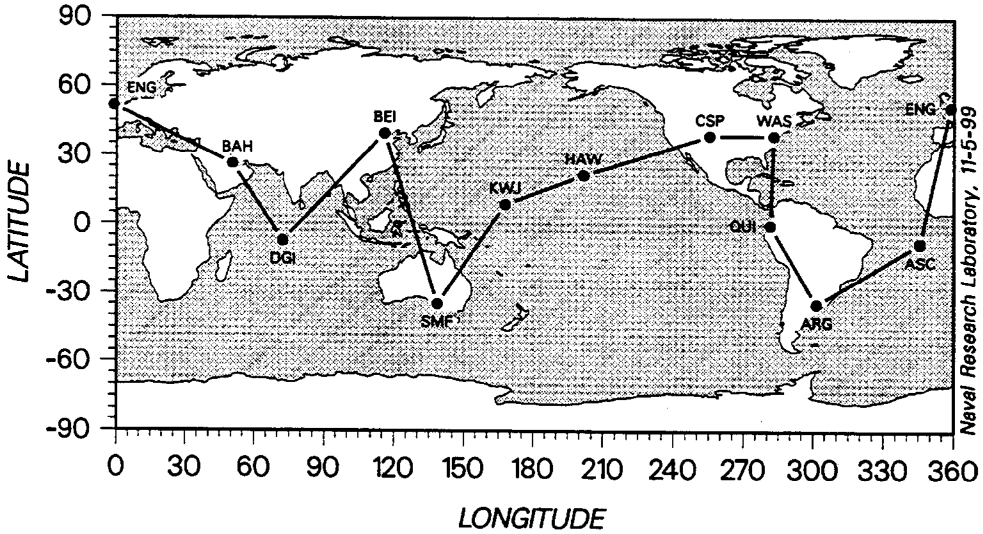

Figure 1

LINKED COMMON-VIEW TIME TRANSFER DIAGRAM USING USAF AND NIMA MONITOR STATIONS

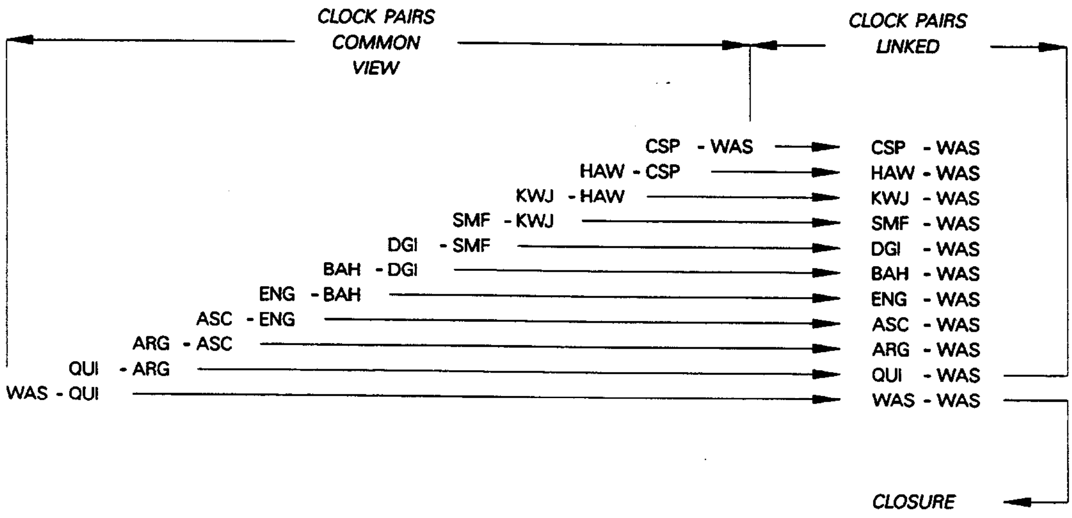

Figure 2

ACCUMULATION OF GAPS IN LINKED COMMON-VIEW TIME TRANSFER FROM
DoD Master Clock Using
Serial Linking

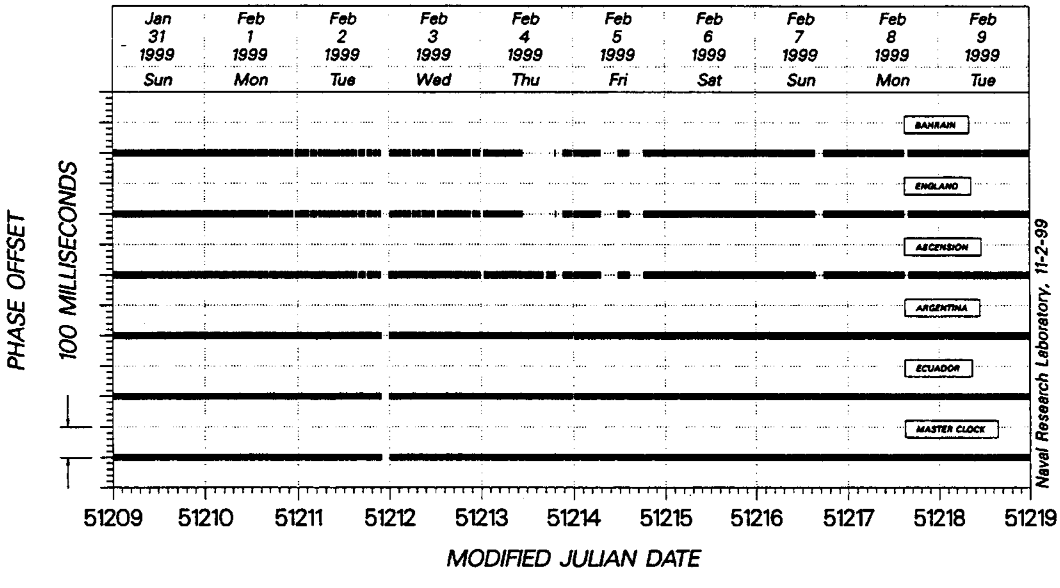

Figure 3

OBSERVATION TIMES POPULATED BY MONITOR SITES

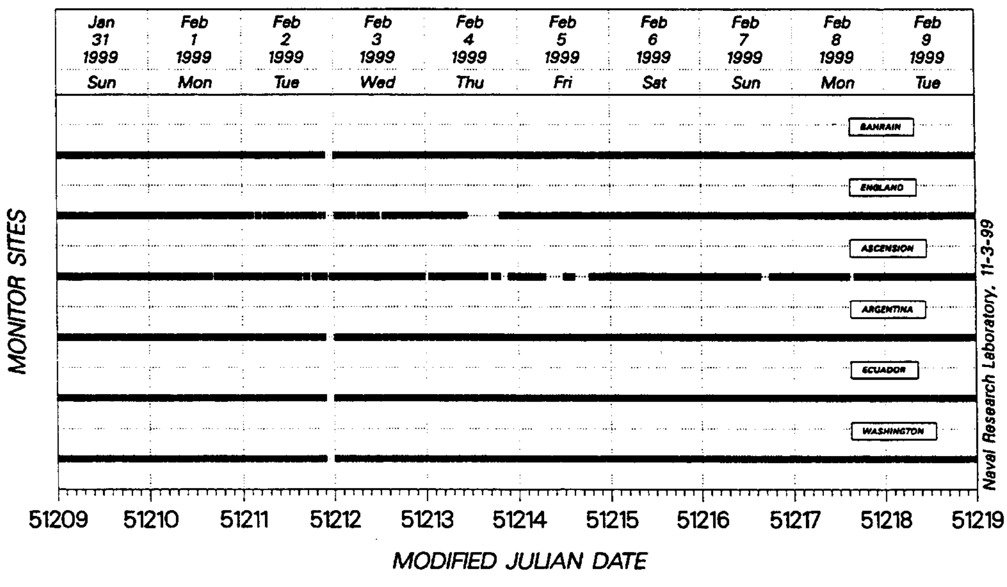

Figure 4

MULTIPLE PATHS USED IN LINKED COMMON-VIEW TIME TRANSFER TO BAHRAIN

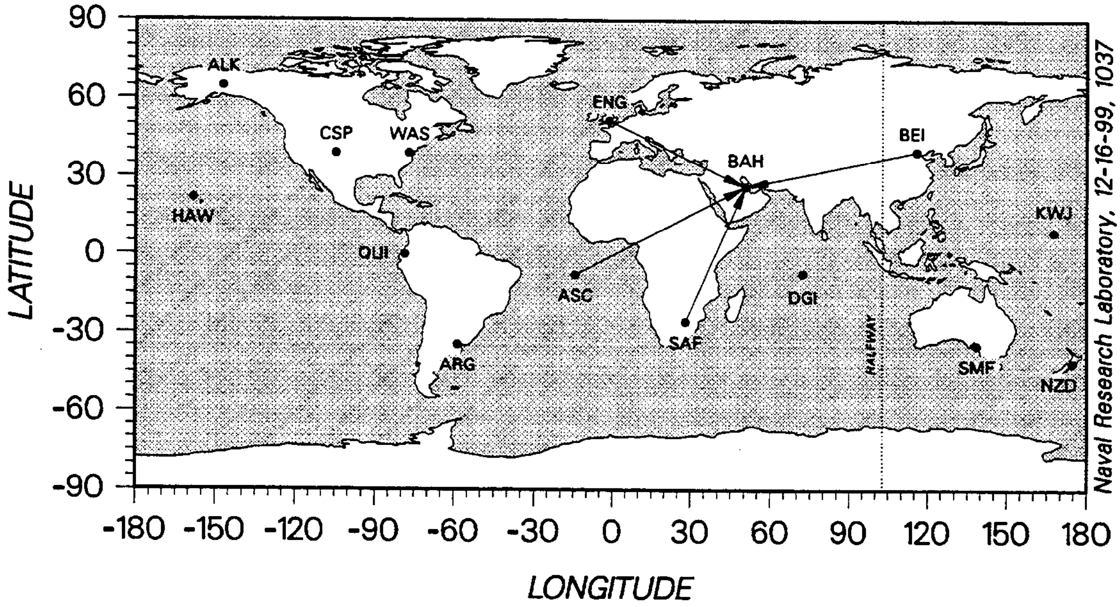

Figure 5

DoD Master Clock Using Single-Path LCVTT Linear Residuals

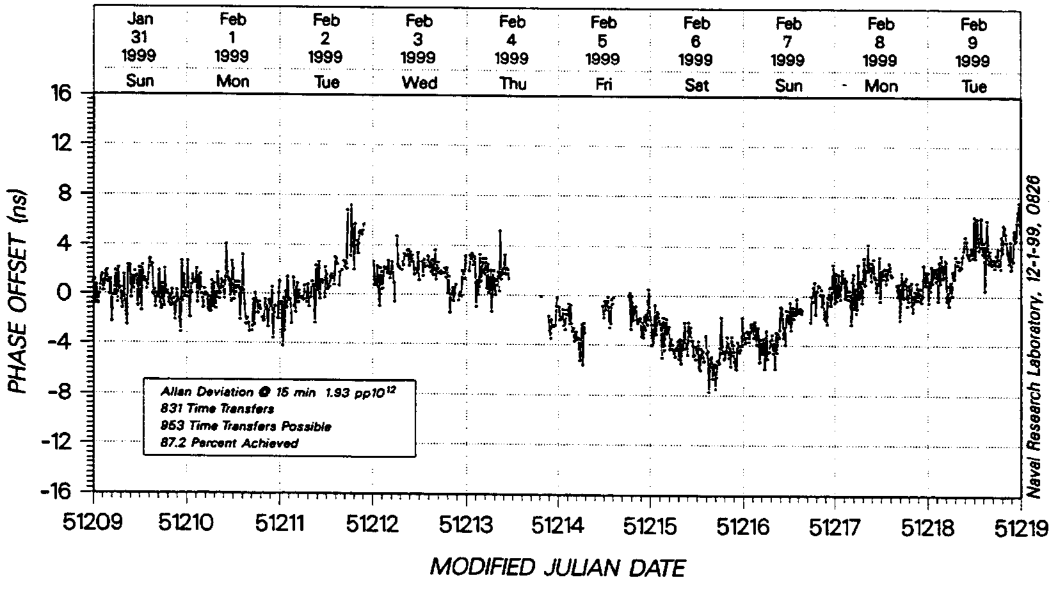

Figure 6

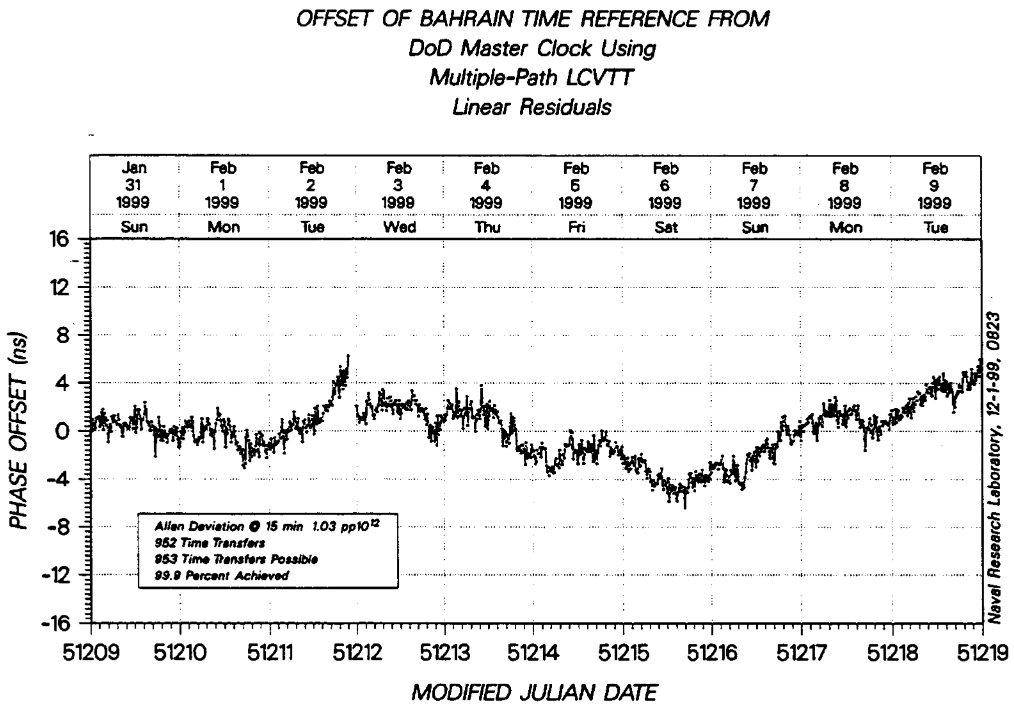

Figure 7

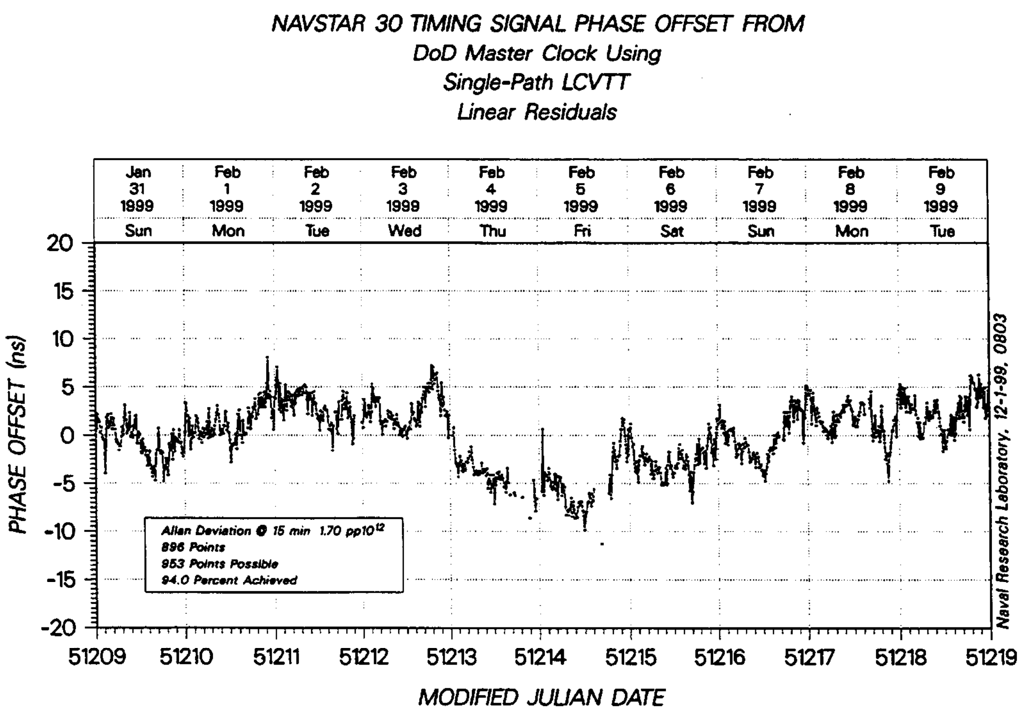

Figure 8

NAVSTAR 30 TIMING SIGNAL PHASE OFFSET FROM
DoD Master Clock Using
Multiple-Path LCVTT
Linear Residuals

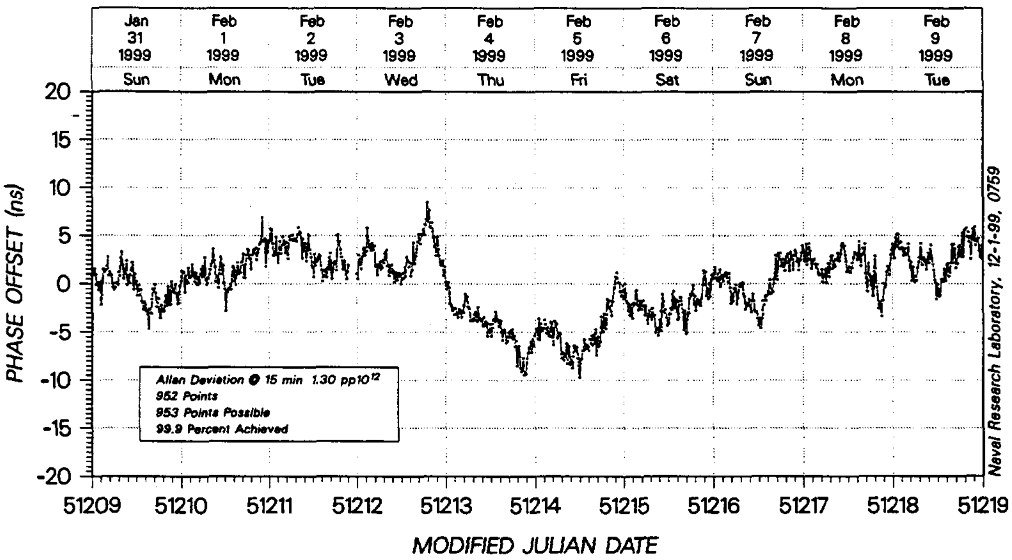

Figure 9

COMMON-VIEW LINKS USED IN
MULTIPLE-PATH LINKED COMMON-VIEW TIME TRANSFER

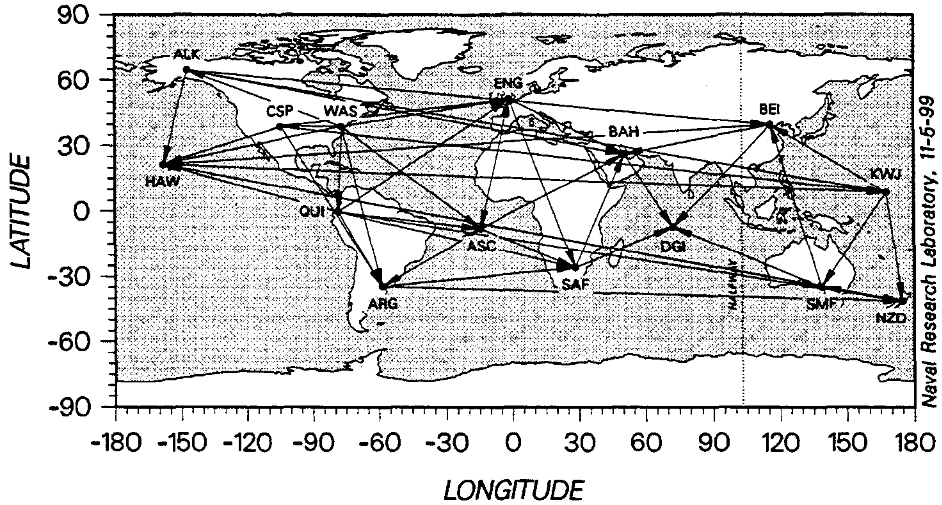

Figure 10